Decision Trees and Fuzzy Logic: A Comparison of Models for the Selection of Measles Vaccination Strategies in Brazil

Lucila Ohno-Machado, MD, PhD, Ronilda Lacson, MD and Eduardo Massad, MD, PhD
Decision Systems Group, Brigham and Women's Hospital, Harvard Medical School
Division of Health Sciences and Technology, Massachusetts Institute of Technology, Boston, MA
Disciplina de Informática Médica, Faculdade de Medicina da Universidade de São Paulo São Paulo, Brazil

ABSTRACT

In 1997, health authorities of the state of São Paulo, Brazil designed a vaccination campaign against measles based on a decision model that utilized fuzzy logic. The chosen mass vaccination strategy was implemented and changed the natural course of the epidemic in that state. We have built a model using a decision tree and compare it to the fuzzy logic model. Using essentially the same set of assumptions about this problem, we contrast the two approaches. The models identify the same strategy as being the best one, but exhibit differences in the ranking of the remaining strategies.

INTRODUCTION

The choice of a vaccination strategy can have a great public health impact, and requires the use of a model that deals with uncertainty [1]. In 1997, a recurrent epidemic of measles reached alarming numbers in the state of São Paulo, Brazil, and a decision model based on fuzzy logic served as the basis for choosing a strategy to selectively immunize children aged 9 months to 6 years, via community health centers.

The purpose of a decision model in this domain was to select the vaccination strategy that (1) maximized the number of susceptible children who were immunized and (2) minimized the number of non-susceptible children who had to be vaccinated.

The fuzzy logic model was chosen for its simplicity and is reported in [1]. Its recommended strategy was successfully implemented. However, alternatives to the fuzzy logic model exist and can employ more traditional probabilistic methods. This includes decision trees, which represent a traditional approach to decision-making that deals with uncertainty and has been widely used in health care applications [2-5].

To contrast the fuzzy logic model, we built a decision tree using the same data and compared the results. We discuss the advantages and disadvantages of using each method in terms of ease of understanding, the assumptions that necessary, and robustness of the models.

MATERIALS AND METHODS

The Problem and Data. Eight possible immunization strategies were considered, with respect to patient age, previous immunization history (susceptible vs. all), and location of immunization service (i.e., mobile unit or community health centers). These eight options are shown in Table 1.

Table 1. Strategies considered.

Strategy	Susceptible 9m-6y	Susceptible 6-14y	All 9m-6y	All 6-14y	Mobile	Health Center
1	X			X	X	X
2	X			X		X
3	X	X			X	X
4		X	X		X	X
5			X	X	X	X
6	X					X
7	X				X	X
8			X		X	X

Experts from the Health Secretariat in São Paulo provided ratings for each of the eight alternatives according to (a) compliance by the communities, (b) health care resources, (c) transportation, and (d) ease of communication with the population. These are the perceived barriers to effective administration of the vaccine to the target population, disregarding the influence of costs. The average rating for each item is shown in Table 2. The rating is just an assessment of the feasibility of each item. A rating close to 0 would indicate that the feasibility was low. There were no instructions to the experts that the ratings might be treated as probabilities.

Table 2. Expert estimates of success for each strategy.

	Compliance	Staff	Transport	Communication
1	0.30	0.30	0.20	0.30
2	0.45	0.60	1.00	0.50
3	0.70	0.50	0.30	0.40
4	0.40	0.40	0.30	0.40
5	0.80	0.20	0.2	0.80
6	0.60	1.00	1.00	0.70
7	0.50	0.60	0.60	0.60
8	1.00	0.70	0.40	1.00

The number of children considered susceptible to measles is 592,272 out of 9,274,320 (6.39%) (see [1]). The total number in each age group is shown in Table 3.

Table 3. Number of children (succeptible and total).

Age	Succeptible	Total
9m	32,175	49,500
10m	24,750	49,500
11m	24,750	49,500
12m	24,750	49,500
1-2	64,061	640,609
3-5	125,786	2,515,711
6-14	296,000	5,920,000

Fuzzy Decision Model

In the fuzzy logic model described in [1], the minimum of the estimates of success for the four categories of barriers to effective vaccination was taken as a proxy for an overall estimate of the technical constraint for each of the eight alternative strategies. In this model, the estimates were not considered to represent probabilities, and no attempt to use probability theory or traditional decision analysis methods was made.

The potential financial costs associated with each alternative strategy were then calculated based on the number of children who were targeted in each age group, multiplied by the technical constraint for that strategy. An estimate of US$2.14 per child over 1 y.o. (who received the measles-mumps-rubella vaccine, or MMR) and US$1.00 for younger children was used. The relative dollar figures were normalized to a 0 to 1 scale.

Relative efficacy for each strategy was calculated as the minimum square difference between the number of children required to receive the immunization and the number who would actually benefit from the immunization, then normalized so that it would also fit into a 0 to 1 scale.

Economic costs and technical constraints were used to determine the overall constraint for each strategy. Relative efficacy was used to represent the goals. In fuzzy decision making, the minimum between goals and contraints is calculated for each strategy, and the strategy resulting in the highest number is chosen as the best decision. In this case, the best alternative was determined to be the sixth strategy. See [1] for details.

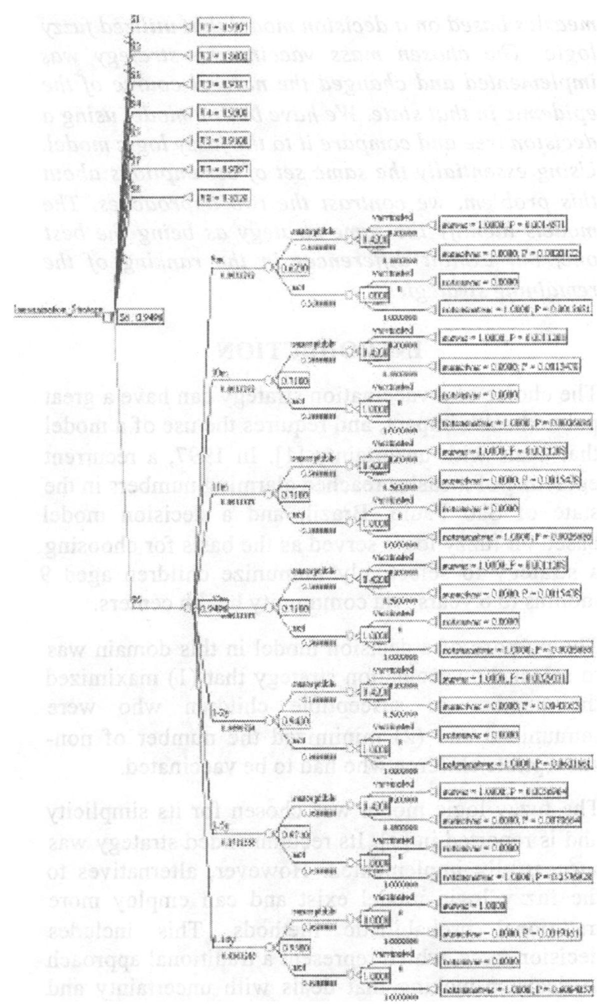

Figure 1. Simplified illustration of the decision tree showing a few nodes.

Decision Tree

In order to make the comparisons fair, we used exactly the same numbers and assumptions from the fuzzy model, and added some other necessary ones. Some of the assumptions were implicit in that model, but we make them explicit in our decision tree. We depict part of the decision tree in Figure 1.

First, we assumed that the experts' ratings for technical constraints could represent probabilities, and made the strong but realistic assumption that the four variables (Compliance, Human resources, Transport, and Communication) were independent. We calculated the probability of success for each age group in a given strategy as being simply the product of the corresponding four ratings. As shown later, a sensitivity analysis indicated that this assumption was not unrealistic for this problem. This was an assumption that was not required by the fuzzy model. We then utilized an assumption from the fuzzy decision model, namely that the relative efficacy was based on a utility scale that promoted maximization of the number of susceptible children immunized, and minimization of the number of non-susceptible children who had to receive the immunization. The utilities for immunizing a non-susceptible child and not immunizing a susceptible child were set to be the same (zero) and so were the utilities for not immunizing a non-susceptible child and immunizing a susceptible child (one). This assumption was implicit in the fuzzy model.

Another assumption in the fuzzy model is that the costs (cost constraints) can be translated into the same scale as the likelihood of success given the perceived barriers to successful implementation (technical constraints). This implies that both the relative magnitude of potential financial costs and the magnitude of perceived technical barriers to implementation (without considering these costs) will have important consequences in terms of defining the best strategy. We performed a cost-effectiveness analysis by ranking the interventions according to cost and calculating the incremental cost per incremental unit of clinical outcome. [6]

RESULTS

The expected value of each strategy in the decision tree, not considering financial costs, was ranked the same as the fuzzy model for the first three best strategies (numbers 6, 7 and 3). The ranking of the remaining strategies was somewhat different. However, given the dominance of the best three alternatives over the other ones, we do not think this constitutes a problem. Table 4 shows the ranked strategies for each model.

A sensitivity analysis was performed for the utility of immunizing a non-susceptible individual, assuming that the utilities of immunizing a susceptible child and not immunizing a non-susceptible one remain the same (one). Likewise, the utility for not immunizing a susceptible child remains at zero. The ranked strategies remain unchanged.

Table 4. Ranked strategies using the two models

Decision Analysis	Fuzzy logic
6	6
7	7
3	3
4	8
1	4
5	1
2	5
8	2

Several sensitivity analyses were performed with regard to the probability of successful immunization of the target group for each of the strategies. This is important because the values used had been expert estimates of successful immunization given some barriers for each strategy and not actual probabilities. The result of the sensitivity analysis on the probability of successful immunization with the sixth strategy is shown in figure 2. The resulting figure reflects the preference for the sixth strategy unless the estimated success decreases to 0.11, which is equal to the estimated success of the seventh strategy. This is obvious when one compares the two strategies, since their difference is solely with respect to adding a mobile unit for the seventh strategy, which affects the resultant experts' estimates of success.

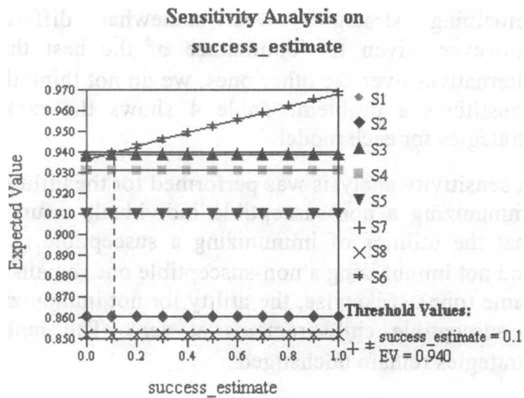

Figure 2: Sensitivity analysis on the probability of successful implementation of the sixth strategy

The other sensitivity analyses revealed that, should the estimate of success for the third strategy increase from 0.04 to 0.20, this would be the preferred approach. Varying the other estimates did not make a difference to the final strategy ranking.

The cost-effectiveness analysis shows that the sixth strategy clearly dominates the others. Table 5 shows the cost ranking comparing the various strategies and their corresponding utilities. The first five strategies have the highest utilities and correspondingly lower costs.

Table 5. Strategies ranked according to cost

Strategy	Cost (US$)	Utility
6	308,758	0.9496
7	370,509	0.9397
3	414,359	0.9387
4	2,743,384	0.9308
1	3,178,223	0.9307
8	3,352,374	0.8528
5	4,730,907	0.9100
2	5,959,168	0.8602

DISCUSSION

The study suggests that the sixth strategy for mass vaccination against measles, targeting susceptible children between 9 months and 6 years of age via health centers, was indeed preferable over all others. This was reassuring, considering that this strategy was chosen and already implemented for the state of Sao Paulo, Brazil. This option was preferred regardless of the analytic method used. Furthermore, the first three preferred strategies were similar for both models.

However, care must be taken in interpreting the results of this study. Several assumptions were made that need further elucidation. First, identification of susceptible children was done using dynamic modeling, similar to the way it was done in the model described for rubella [7]. This predictive model was assumed to be perfectly discriminatory (i.e., able to identify all susceptible cases). This is probably not the case in real life, yet for simplicity, it was incorporated in both of the models described.

In the decision analysis model, all assumptions were explicitly stated *a priori*, as the decision tree was being created. Utilities were chosen based on the implied goals of this project, using scientifically reasonable assumptions. However, assigning equal weights, both to immunizing a non-susceptible child and not immunizing a susceptible child, may not necessarily reflect the true values of the study population. In addition, we had assumed that the expert estimates of success in implementing each strategy given several potential barriers were true probabilities of success. Moreover, we assumed that each estimate was independent and equally weighted. All these assumptions were addressed in the analysis by performing a sensitivity analysis in order to verify the robustness of the results, while varying these key assumptions.

Fortunately, the sixth strategy was clearly dominant in terms of cost and outcome in the decision analytic model. This precludes having to decide whether other options would be preferred for a greater cost in an incremental cost-utility analysis.

The fuzzy logic model makes no assumption about utilities or probabilities. However, it assumes that the expert estimates are comparable in scale, both for each expert between variables and between experts for each variable. Furthermore, the expert opinions of successful implementation given several technical barriers were considered without regard to their interdependence and accompanying costs. Moreover, successful implementation given several variables is implicitly assumed to depend on the lone variable most deterrent to success. Thus, if fuzzy logic were used without adding cost as an equal factor in the analysis, the best strategy would have been the third one, where all susceptible children, from 9 months to 14 years of age, were immunized from health centers and mobile units.

Fuzzy logic assumes that costs and effects have comparable scales, thus limiting its discriminatory effect on either dimension. For example, if there were only two strategies and the estimated likelihood of success for the first one were several orders of magnitude higher than that for the second, but both costs were lower than the effectiveness values, the cost would be the sole determinant of the best strategy. More importantly, a sensitivity analysis cannot be performed to determine the robustness of the resulting model. Thus, if the expert opinions were not accurate and verifiable, the effect could be a huge variance in the model's preferred strategy.

Comparing decision analytic approach and fuzzy logic by ease of acceptance, we imagine that it might be easier to present the result of the decision analysis because strategies are compared against each other in one diagram or decision tree. In addition, all assumptions are explicitly stated and easily tested with a sensitivity analysis. Although quantitative assessment of the explanatory power of decision analytic methods has not been performed in this study, this potential advantage has been reported by other authors in unrelated domains [8,9]. The major drawback to widespread use of this method is physicians' lack of familiarity with and skepticism towards probabilistic concepts [6]. However, fuzzy logic makes multiple implicit assumptions that may be more of a black box for physicians, thus making it even harder to follow the logical decision steps.

CONCLUSION

In conclusion, it was possible to model uncertainty when choosing between various alternatives for the best measles vaccination strategy in Brazil. This was demonstrated using a decision analysis model. The best strategy was identical to the previously published approach using fuzzy logic. The assumptions were slightly different for the decision analysis and fuzzy logic models. The three alternatives considered best by the fuzzy logic and the decision analysis models were the same, but these models resulted in different rankings for the remaining alternatives. It is impossible to say which model would produce better results.

ACKNOWLEDGMENTS

This project was funded in part by grant 1D43TW01279-01 from the Fogarty International Center and the National Library of Medicine,, National Institutes of Health. The original work for the fuzzy decision model was funded by grant PRONEX 4196093700. Prof. Robert Greenes provided valuable suggestions to this project.

REFERENCES

[1] Massad E, Burattini MN, Ortega NR. Fuzzy logic and measles vaccination: designing a control strategy. Int J Epidemiol. 1999 Jun;28(3):550-7.

[2] Col NF, Eckman MH, Karas RH, Pauker SG, Goldberg RJ, Ross EM, Orr RK, Wong JB. Patient-specific decisions about hormone replacement therapy in postmenopausal women. JAMA, 1997; 277(14): 1140-7.

[3] Mason JJ, Owens DK, Harris RA, Cooke JP, Hlatky MA. The role of coronary angiography and coronary revascularization before noncardiac vascular surgery. JAMA, 1995; 273(24): 1919-24.

[4] O'Meara JJ, McNutt RA, Evans AT, Moore SW, Downs SM. A decision analysis of streptokinase plus heparin as compared with heparin alone for deep vein thrombosis. NEJM, 1994; 330(26): 1864-9.

[5] Ohno-Machado L, Parra E, Henry SB, Tu SW, Musen MA. AIDS2: A decision-support tool for decreasing physicians' uncertainty regarding patients' eligibility for HIV treatment protocols. Proceedings of the Seventeenth Annual Symposium on Computer Applications in Medical Care, 429-33, 1993.

[6] Detsky AS, Naglie IG. A clinician's guide to cost-effectiveness analysis. Ann of Int Med., 1990; 113(2): 147-54.

[7] Massad E, Burattini MN, Azevedo Neto RS de, Yang HM, Coutinho FAB, Zanetta DMT. A model-based design of a vaccination strategy against rubella in a non-immunized community of Sao Paulo State, Brasil. Epidemiol Infect, 1994; 112:579-94.

[8] Langlotz CP, Shortliffe EH, Fagan LM. A methodology for generating computer-based explanations of decision-theoretic advice. Med Decis Making 1988;8(4):290-303.

[9] Sanders GD, Hagerty CG, Sonnenberg FA, Hlatky MA, Owens DK. Distributed decision support using a web-based interface: prevention of sudden cardiac death. Med Decis Making. 1999;19(2):157-66.